

# FINAL TECHNICAL REPORT

Ocean Acoustic Tomography with Moving Sources and Receivers

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## I. Work summary

The fundamental goal of the research performed under this contract has been to determine the precision with which the ocean mesoscale sound speed field can be measured using acoustic techniques. The basic idea is straightforward: to use acoustic sources and/or receivers suspended from ships to provide dense sets of acoustic ray paths in order to construct sound speed maps with mesoscale resolution over large areas. We named the technique *Moving Ship Tomography*.

Determining the fraction of ocean sound speed variance that can be measured using acoustic techniques is of critical importance in potential applications to passive and active ASW systems. The ocean sound speed field is required as input for matched field (and other) processing of long range acoustic transmissions. The ability to measure the ocean sound speed (temperature) field with mesoscale resolution is also important to the study of eddy kinematics and dynamics, to verify numerical models, and to study data assimilation techniques.



Implementation of moving ship tomography required the solution of a number of technological problems. Instrument positions need to be determined to ±10 m, using a combination of differential GPS and acoustic navigation. The signal processing techniques and algorithms need to work when the sources and/or receivers are moving at significant speeds. The inversion techniques used to convert travel time data to the 3-D sound speed (temperature) field need to take account of the time-dependence in the ocean and in the data. Our research has therefore involved an extensive experimental program, as well as related theoretical analyses and simulations. A total of eight research cruises have been conducted:

(1) May 1988: Preliminary Equipment Test

(2) September-October 1988: Greenland Sea Mooring Deployment/Moving Ship Tomography Preliminary Engineering Test (Partial Support)

(3) June 1989: SLICE89 Source Deployment (Partial Support)

(4) August-September 1989: Greenland Sea Mooring Recovery/Moving Ship Tomography Full-Scale Engineering Test (Partial Support)

(5) September 1989: SLICE89 Source Recovery (Partial Support)

(6) March 1991: AMODE Mooring Deployment

(7) June-July 1991: AMODE Moving Ship Tomography Cruise

(8) March 1992: AMODE Mooring Recovery

While analysis of the data collected on these cruises is continuing, all indications are that we have obtained the experimental data necessary to determine the answer to our principal question: What fraction of the ocean sound speed variance can be determined using acoustic techniques? Is it 90% or 99%?

The results obtained to date are given in the publications listed below. The research reported here was performed jointly with B. Howe, J. Mercer, and R. Spindel of the Applied Physics Laboratory at the University of Washington and with T. Birdsall and K. Metzger of the University of Michigan.

## II. Technical Reports

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| 1. | Bader, C.M., B.M. Howe, J.A. Mercer, P.F. Worcester, B.D. Cornuelle, and J. Lynch, "CTD, XBT, and XSV Data from the Greenland Sea: R/V *Knorr* Cruise 8809 (6 September – 4 October 1988) and R/V *Endeavor* Cruise EN200 (3 August – 10 September 1989), Applied Physics Laboratory, University of Washington, Technical Memorandum APL-UW TM3-91 (1991) | TECHNICAL MEMORANDUM |
| 2. | Howe, B.M., B.D. Cornuelle, J.A. Mercer, K. Metzger, and P.F. Worcester, "Acoustic Mid-Ocean Dynamics Experiment: 1991 Moving Ship Tomography Cruise," Applied Physics Laboratory, University of Washington, Technical Memorandum APL-UW TM18-91 (1991) | TECHNICAL MEMORANDUM |
| 3. | Cornuelle, B.D., P.F. Worcester, J.A. Hildebrand, W.S. Hodgkiss, Jr., T.F. Duda, B.M. Howe, J.A. Mercer, and R.C. Spindel, "Vertical slice ocean acoustic tomography at 1000-km range in the North Pacific Ocean," Scripps Institution of Oceanography Reference Series 92-17 (1992). | TECHNICAL REPORT |

## III. Publications

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| 1. | Cornuelle, B., W. H. Munk, and P. F. Worcester, "Ocean acoustic tomography from ships," *J. Geophys. Res.*, *94*, 6232–6250 (1989). | RESEARCH ARTICLE |
| 2. | Howe, B.M., J.A. Mercer, R.C. Spindel, and P.F. Worcester, "Accurate positioning for moving ship tomography," *OCEANS '89 Conference Record*, Seattle, WA, Sept. 18-21, 880–886 (1989). | RESEARCH ARTICLE |
| 3. | Worcester, P.F., B.D. Dushaw, and B.M. Howe, "Gyre-scale current measurements using reciprocal acoustic transmissions," *Proc. IEEE Fourth Working Conference on Current Measurement*, Clinton, Maryland, April 3–5, 1990, 65–70 (1990). | RESEARCH ARTICLE |
| 4. | Howe, B.M., J.A. Mercer, R.C. Spindel, P.F. Worcester, J. A. Hildebrand, W. S. Hodgkiss, Jr., T.F. Duda, and S. M. Flatté, "SLICE89: A single slice tomography experiment," in *Ocean Variability and Acoustic Propagation*, Proc. of the Workshop on Ocean Variability and Acoustic Propagation, La Spezia, Italy, June 4–8, 1990, J. Potter and A. Warn-Varnas, Eds., Kluwer Academic Publishers, 81–86 (1991). | RESEARCH ARTICLE |

5. Worcester, P.F., B.D. Dushaw, and B.M. Howe, "Gyre-scale reciprocal acoustic transmissions," in *Ocean Variability and Acoustic Propagation*, Proc. of the Workshop on Ocean Variability and Acoustic Propagation, La Spezia, Italy, June 4–8, 1990, J. Potter and A. Warn-Varnas, Eds., Kluwer Academic Publishers, 119–134 (1991). — RESEARCH ARTICLE

6. Duda, T.F., S.M. Flatté, J.A. Colosi, B.D. Cornuelle, J.A. Hildebrand, W.S. Hodgkiss, Jr., P.F. Worcester, B.M. Howe, J.A. Mercer, and R.C. Spindel, "Measured wave-front fluctuations in 1000-km pulse propagation in the Pacific Ocean," *J. Acoust. Soc. Am.*, *92*, 939–955 (1992). — RESEARCH ARTICLE

7. Dushaw, ,B.D., P.F. Worcester, B.D. Cornuelle, and B.M. Howe, "On equations for the speed of sound in seawater," *J. Acoust. Soc. Am.* (in press, 1992). — RESEARCH ARTICLE

8. Dushaw, B.D., P.F. Worcester, B.D. Cornuelle, and B.M. Howe, "Variability of heat content in the Northcentral Pacific in summer 1987 determined from long-range acoustic transmissions," *J. Phys. Oceanogr.*, (submitted, 1992). — RESEARCH ARTICLE

## IV. Abstracts

1. Worcester, P.F., B. Cornuelle, B.M. Howe, and W. Munk, "High resolution ocean acoustic tomography," *J. Acoust. Soc. Am.*, *82*, Suppl. 1, S43 (1987). — INVITED ABSTRACT

2. Worcester, P.F., B.M. Howe, and B.D. Dushaw, "The 1987 gyre-scale reciprocal acoustic transmission experiment," *EOS* (Autumn 1988 AGU meeting). — ABSTRACT

3. Worcester, P.F., B.D. Dushaw, and B.M. Howe, "North Pacific gyre-scale reciprocal acoustic transmission experiment," *J. Acoust. Soc. Am. Suppl. 1*, *88*, S116–S117 (1990). — INVITED ABSTRACT

4. Howe, B.M., J.A. Mercer, R.C. Spindel, P.F. Worcester, B.D. Cornuelle, W.H. Munk, T.G. Birdsall, and K. Metzger, Jr., "An engineering test of moving ship tomography in the Greenland Sea," *J. Acoust. Soc. Am. Suppl. 1*, *88*, S140–S141 (1990). — INVITED ABSTRACT

5. Duda, T.F., S.M. Flatté, P.F. Worcester, B.D. Cornuelle, J.A. Hildebrand, W.S. Hodgkiss, Jr., B.M. Howe, J.A. Mercer, and R.C. Spindel, "A single slice tomography experiment using a long vertical array of receivers," *J. Acoust. Soc. Am. Suppl. 1*, *88*, S117 (1990). — INVITED ABSTRACT

6. Flatté, S.M., T.F. Duda, J. Colosi, J. Hildebrand, W. Hodgkiss, P.F. Worcester, B.D. Cornuelle, B.M. Howe, J. Mercer, and R. Spindel, "Wavefront fluctuations in the 1000-km SLICE89 experiment," *J. Acoust. Soc. Am.*, *89*, 1962 (1991). — INVITED ABSTRACT

7. Cornuelle, B.D., P.F. Worcester, J.A. Hildebrand, W.S. Hodgkiss, Jr., T.F. Duda, S.M. Flatté, J. Colosi, B.M. Howe, J.A. Mercer, and R.C. Spindel, "A single slice tomography experiment using a long vertical array of receivers," XX General Assembly of the IUGG, Vienna, Austria, 11–24 August, 1991. — ABSTRACT

8. Worcester, P.F., B.D. Dushaw, and B.M. Howe, "North Pacific gyre-scale reciprocal acoustic transmission experiment," XX General Assembly of the IUGG, Vienna, Austria, 11–24 August, 1991. — ABSTRACT

9. Colosi, J.A., T.F. Duda, S.M. Flatté, B.D. Cornuelle, J.A. Hildebrand, W.S. Hodgkiss, P.F. Worcester, B.M. Howe, J. Mercer, and R. Spindel, "Wavefront fluctuations in the 1000-km Slice89 experiment," *Eos, Transactions, American Geophysical Union, Suppl., 72*, AGU 1992 Ocean Sciences Meeting, New Orleans, Louisiana, January 27–31, 1992 (Dec. 17, 1991). ABSTRACT

10. Dushaw, B.D., P. F. Worcester, B. D. Cornuelle, and B. M. Howe, "On equations for the speed of sound in seawater," *J. Acoust. Soc. Am., 91, Pt. 2*, ASA Spring 1992 Meeting, Salt Lake City, Utah, May 11–15, 1992, 2391 (1992). ABSTRACT

11. Dushaw, B.D., P.F. Worcester, and B.D. Cornuelle, "Variability of heat content in the North-central Pacific in summer 1987 determined from long-range acoustic transmissions," *J. Acoust. Soc. Am.*, ASA Fall 1992 Meeting, New Orleans, LA, Oct. 31–Nov. 4, 1992 (submitted, 1992). ABSTRACT